SPECIAL REPORT 99-8

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Flow Control to Manage River Ice

Andrew M. Tuthill

July 1999

Abstract: This report describes flow-control methods for reducing ice problems in rivers. Objectives include reducing ice interference with winter hydroelectric production and navigation, ice jam flood mitigation, as well as ensuring minimum winter flows for fish and water supply. The winter season is divided into three periods. During early winter, the main objective of flow control is to promote the rapid formation of a smooth, stable ice cover. For the midwinter period, the aim of the river regulation is to maintain an intact ice cover and avoid premature ice breakup. During the final winter period, the goal is to minimize adverse effects of ice breakup. Examples illustrate the methods and objectives, emphasizing innovative approaches. Available flow regulation planning tools are described and valuable research directions identified.

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Prepared for
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PREFACE

Andrew M. Tuthill, Research Hydraulic Engineer, Ice Engineering Research Division, U.S. Army Cold Regions Research and Engineering Laboratory, prepared this report. The Civil Works, Cold Regions Engineering Program, work unit, *Ice Mitigation Measures in Navigable Rivers*, funded this work.

Dr. J.-C. Tatinclaux and Kathleen White of CRREL provided technical reviews, and Mark Hardenberg was editor. Randy Crissman of the New York Power Authority's Niagara Falls project edited the section on Lake Erie and the upper Niagara River.

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Flow Control to Manage River Ice

ANDREW M. TUTHILL

INTRODUCTION

Winter flow control can reduce ice problems on rivers and waterways, benefiting the hydroelectric and navigation industries, and reducing the threat of ice jam flooding. Winter flow regulation can also reduce ice interference with the operation of locks and dams and mitigate ice problems upstream and downstream of water storage reservoirs. More recently, the interrelationships among flow regulation, ice processes, and winter fish habitat have gained increasing attention.

Flow reductions during critical early winter periods can speed the formation of a juxtaposed ice cover, decreasing the open water area for frazil ice production, and reducing the occurrence of freezeup ice jams and hanging dams. An additional benefit is that a juxtaposed cover is relatively smooth, offering less resistance to flow than the rougher, "shoved" ice cover that might form in the absence of flow control. During the last three or four decades, many hydroelectric producers in the northern U.S., Canada, and northern Europe have regulated flow during critical early winter periods to reduce ice-related head losses, at substantial economic gains. In addition to maximizing winter hydroelectric production, projects may control outflow to reduce the occurrence of freezeup ice jams and related flooding. The successful performance of ice retention booms may also depend on flow reductions during critical periods. Finally, the rapid formation of a smooth ice cover can benefit winter navigation by minimizing frazil ice production and ice cover thickness, thus reducing ice interference with navigation projects such as locks and dams.

During the midwinter period, flow control at dams can smooth and maintain the newly formed ice cover for the benefit of winter hydroelectric production and ice jam flood control. Following ice cover formation, gradual increases in flow smooth the underside of the ice cover, reducing hydraulic resistance and ice-related head losses at the intakes. Once a stable freezeup cover has formed, hydroelectric projects often return to their open-water generating capacity without adverse effects.

Where ice jam flood potential exists, project operators may try to minimize rapid fluctuations in stage and discharge that could break up the midwinter ice cover. However, this practice often conflicts with hydroelectric operations, where large daily fluctuations may be required to meet peak demands. In some situations, a hydroelectric diversion may be great enough to reduce the ice conveyance capacity of a river reach and actually contribute to ice jamming. The winter pool level of water supply and flood control reservoirs can affect the location and extent of freezeup ice jams on tributary streams.

Passing brash ice and flows at navigation projects while maintaining minimum pool levels presents additional operational challenges. During midwinter breakups, passing ice without damaging river structures or threatening navigation is an important operational issue. Finally, maintaining minimum channel depths for navigation and providing water supply and in-stream flow requirements for fish during low-flow periods are important midwinter flow-control issues.

Flow control can influence the timing and sequence of final river breakup and subsequent ice jams. The upstream pool level at a dam at the

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time of breakup can affect the stopping location of an ice run from upstream. Also, reservoir releases as a result of winter runoff events may influence breakup ice jam occurrence and severity in downstream channels. In addition, planned releases from river dams and reservoirs can delay or accelerate the breakup process in downstream reaches, depending on the ice-control objectives.

This report describes winter flow-control methods chronologically, starting with the early winter ice-formation period, followed by the midwinter ice-maintenance period, and concluding with the late winter–early spring ice-breakup period. Examples illustrate flow-control methods and their ice-control objectives. The report summarizes the current state of the art in flow-control methods to manage ice and the conclusions highlight areas where innovative methods and future research might have the greatest benefit in terms of managing river ice.

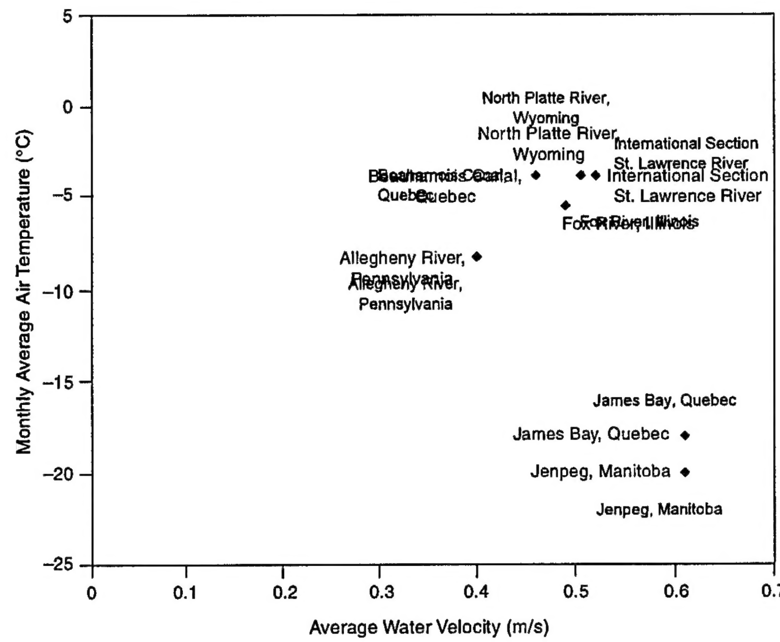

Figure 1. Monthly average air temperature vs. average water velocity during flow cutbacks for ice covers formation. Note that the James Bay and Jenpeg structures are located at about latitude 55° north while the others are located south of 45° north.

EARLY WINTER ICE-FORMATION PERIOD

Hydraulic conditions for ice formation

Flow control for ice formation usually requires that discharge be reduced at a river structure to promote the rapid growth of a relatively thin, hydraulically smooth ice cover by ice floe juxtaposition. In this dynamic process, frazil pans and ice floes come to rest, edge to edge, at the upstream border of the ice accumulation without underturning or being entrained underneath by the flow. Once a stable ice cover has formed, discharge can be gradually raised to open-water levels.

The accepted criteria for ice cover progression by juxtaposition, based on experience and theory, are a maximum water velocity of about 0.70 m/s and a Froude number* of less than 0.1 (Perham 1983). Under average early winter air temperatures in the northern tier of the U.S., optimal hydraulic conditions for rapid ice cover formation by juxtaposition are a velocity of about 0.46 m/s and a Froude number of 0.06 (Perham 1983, Jain et al. 1993). In colder, more northerly regions, the optimal ice-formation velocity is somewhat higher, as shown in Figure 1.

Velocity alone has been used as an ice-cover-formation criterion as well. In reaches where water velocities are at or below about 0.11 m/s, thermally grown sheet ice or border ice would be expected to form rather than a juxtaposed ice cover. At velocities between about 0.70 and 1.5 m/s, a thicker "shoved" ice accumulation usually forms. In this velocity range, instead of accumulating edge to edge, ice pieces typically underturn at the upstream border of the stationary ice cover. Arriving floes may also be entrained by the current to deposit on the underside of the accumulation in the form of hanging dams. A shoved ice cover is usually much thicker and hydraulically rougher than a juxtaposed cover, resulting in greater head losses. Also, for the same ice supply, the shoved cover is shorter, leaving a larger open water area upstream to produce frazil. These factors make the shoved ice cover less desirable than a juxtaposed ice cover for hydroelectric

* Froude number: $F = v/\sqrt{gh}$ where v = average water velocity; g = acceleration due to gravity; and h = average flow depth.

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production, winter navigation, and ice jam flood control. In most cases, reaches where water velocity exceeds about 1.5 m/s will remain open all winter.

Flow cutbacks for ice formation at hydroelectric projects

Major hydroelectric producers on northern rivers reduce flow through their power stations at critical times to promote ice cover growth upstream of their intakes. The goal is to form an ice cover by the juxtaposition of arriving frazil pans and floes. Because the flow reduction causes a temporary decrease in electrical production, it should be as short as possible, and take place at the optimum time for rapid ice cover formation. From the standpoint of winter-long hydroelectric production at a large facility, the savings resulting from flow control for ice management can be substantial.

Operators use a number of strategies to determine optimal timing and duration of flow cutbacks. These include monitoring air and water temperatures and weather trends. Water surface elevations (WSE) are monitored at points upstream of generating facilities to detect the onset of ice-related head losses or hanging dams. Field observations, both from the ground and the air, are used to detect border ice and floating ice, and, later, the spatial extent and condition of the progressing ice cover. Theoretical methods and numerical models have also been used successfully to predict the timing of ice occurrence and ice cover progression, giving operators some lead time to plan their flow reductions. Flow control for ice cover formation may require basin-wide coordination among hydroelectric producers and water-control organizations.

Four examples illustrating important aspects of flow control at the hydroelectric projects are listed in Table 1. The first two are located on the St. Lawrence River between Lake Ontario and Montreal and the second two are in northern Canada.

St. Lawrence River: New York, Ontario, and Quebec

For the past three decades, hydroelectric producers on the St. Lawrence River have used flow control in conjunction with ice booms to promote rapid, early winter ice cover formation upstream of the power stations at the International Section and on the Beauharnois Canal. The timing and magnitude of the flow regulation is based on weather forecasts, and air and water temperature, as well as the position of the edge of the ice cover as it progresses upstream from the dam. The overall goal is to prevent ice jams and maximize winter hydroelectric production. The International Joint Commission regulates flow in the Great Lakes and St. Lawrence River, with the overall goals of maintaining water levels and preventing flooding. There is no winter navigation on the St. Lawrence upstream of the port of Montreal.

International Section

Six booms are installed annually on the International Section of the St. Lawrence, 64 km upstream of the 3200-MW Moses-Saunders Power Dam, near Massena, New York (Fig. 2). The project is

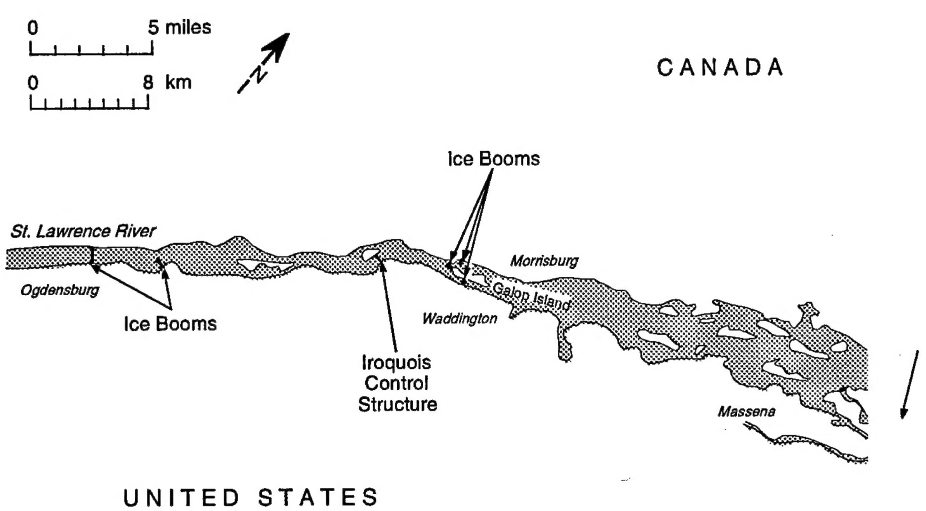

Figure 2. International Section of the St. Lawrence River.

Table 1. Flow control for ice cover formation at major hydroelectric projects.

River/Reach	*Structure*	*Generating capacity (MW)*	*Average discharge before cutback (m^3/s)*	*Average discharge during cutback (m^3/s)*	*Water velocity during cutback (m/s)*	*Froude Number during cutback*	*Ice-control structures*	*Factors influencing timing and duration of flow reduction*
St. Lawrence/ International Section	Moses-Saunders Dam	3200	6510	6230	0.52	0.05	Six ice booms	T_a, T_w, WSE, aerial obs., field meas. t_i, basinwide coordination.*
St. Lawrence/ Beauharnois Canal	Beauharnois Dam	1600	6650	4530	0.46	0.05	Six ice booms	T_a, T_w, WSE, field obs., basinwide coordination, boom force monitoring.
Lake Winnipeg Regulation/ Nelson River	Jenpeg control structure	3600	2550	1650	≤0.61	0.070	Ice boom	$T_a \leq 20°C$, wind, weather forecast, WSE, field obs., basinwide coordination.
James Bay/ La Grande River complex	Three power stations	10,270	4300	1420	≤0.61	0.06		T_a, T_w, WSE, field obs., basinwide coordination, Ice formation prediction model.

*T_a = Air temperature.
T_w = Water temperature.
WSE = Water surface elevation.
t_i = Ice thickness.

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operated jointly by the New York Power Authority (NYPA) and Ontario Hydro (OH). The ice booms and the flow-control measures were adopted following massive ice jams that formed during the first season of operation of the Moses-Saunders Dam in 1958–59. As a result of the jams, discharge through the power stations on the St. Lawrence was reduced by about 1130 m^3/s for most of the winter, water intakes downstream at Montreal were above water, and upstream property along Lake Ontario was threatened by flooding.

Flow at the dam is adjusted according to weather conditions, air and water temperatures, and the location of the edge of the ice cover as it progresses upstream. Although the average cutback flow of 6230 m^3/s is not significantly lower than the long-term average January flow of 6510 m^3/s (Table 1), outflow from Lake Ontario during the early winter can be as high as 8490 m^3/s (New York Power Authority 1970). When the ice cover on Lake St. Lawrence reaches Morrisburg, flow at the Moses-Saunders Dam is reduced if air temperature is at or below –8°C, to allow a juxtaposed ice cover to progress up this higher velocity reach. A quality ice cover cannot form in this reach at higher air temperatures, even at the cutback discharge (Wigle et al. 1981). As the cover progresses upstream around the Galop Island, where four booms are located, discharge is regulated to maintain surface velocities of about 0.52 m/s (Perham 1974). When the cover reaches the Iroquois Control Structure, the gates are lowered into the water to promote continued upstream progression towards Ogdensburg, where two additional booms are located. Once the ice cover has formed and stabilized, discharge is returned to seasonal levels.

Beauharnois Canal

Between the International Section and Montreal, the Beauharnois Canal diverts between 3960 and 7360 m^3/s of the St. Lawrence River discharge through the Hydro Quebec 1600-MW Beauharnois Power Station. In early winter, flow through the turbines is reduced to about 4530 m^3/s to allow an ice cover to form behind a series of six ice booms installed along the 24-km length of the canal. Operators at Beauharnois have found that the optimum water velocity for the rapid formation of a smooth ice cover is 0.46 m/s (Perham and Racicot 1975). The timing and duration of the flow reduction is determined through field monitoring, which is similar to the program of NYPA and OH on the International Section. In addition, anchor lines on the forebay boom are equipped with load cells for continuous force measurement. The highest forces are found during the early stages of the ice-formation period, as an unconsolidated ice cover forms behind the boom. At this time, discharge is maintained at the cutback level. Once the ice cover consolidates and freezes to the channel sides, the measured boom force falls off, indicating that the discharge can be increased. The boom load cells are also used to time flow reductions during ice cover breakup. Ice management at Beauharnois increases annual winter hydroelectric production by an estimated 200 MW (Perham and Racicot 1975).

Northern Canada: Lake Winnipeg Diversion

The Jenpeg Control Structure at a latitude of 54°N regulates the outflow from Lake Winnipeg, feeding the large hydrostations on the lower Nelson River. These stations have a combined generating capacity of about 3600 MW. An ice stabilization program that includes a flow cutback during November is estimated to save Manitoba Hydro C$2 million annually (Zbigniewicz 1997). In addition to flow control, the program includes monitoring of weather forecasts, discharges, and water levels; surveying ice conditions from the air; and installing an ice boom upstream of the Jenpeg forebay each year. When border ice and a high concentration of frazil pans appear upstream of the boom, operators reduce flow from 2550 to 1670 m^3/s, which lowers water velocities to about 0.61 m/s. Additional requirements for flow reduction are an extended forecast for clear skies, northerly winds, and air temperatures of –20°C or below. Because the cutback at Jenpeg reduces the electrical production on the lower Nelson River Stations during the peak demand period of December, it must be as brief as possible.

Northern Canada: La Grande River Complex

Three powerhouses on the La Grande River Complex east of James Bay in Quebec at latitude 53°N have a combined generating capacity of 10,270 MW. In the 48-km-long reach between the first two stations, a November flow reduction from 4300 to 1420 m^3/s promotes the rapid formation of a smooth ice cover. Average water velocity during the cutback is about 0.61 m/s. In addition to field monitoring of air and water temperatures and water levels, an ice cover prediction model aids operators on the timing and magnitude of the flow changes (Drouin and Hausser 1984).

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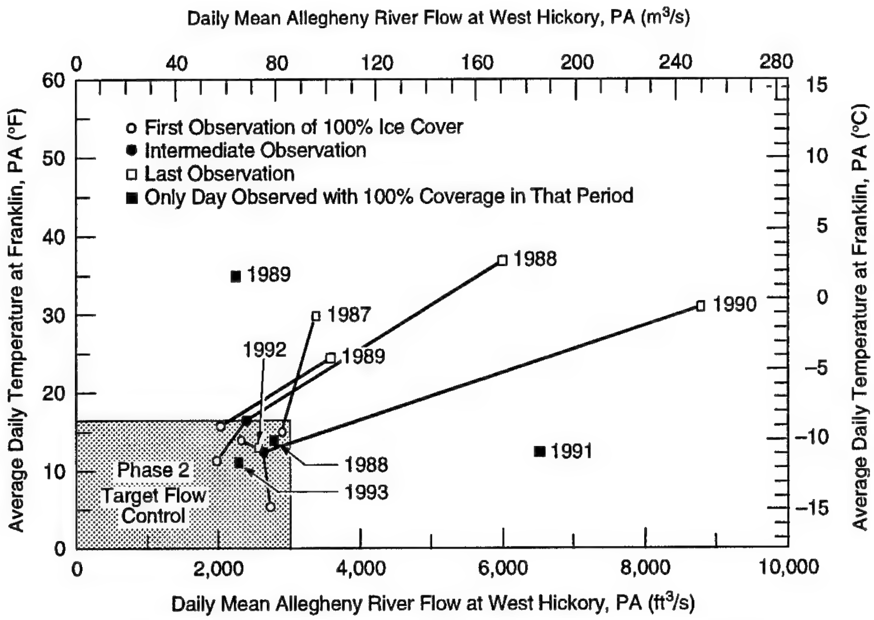

Figure 3. Observed river discharge and air temperatures at the Allegheny River ice boom during periods of complete ice cover formation. (After Daly and Gooch 1994.)

Early winter flow regulation to control freezeup ice jam flooding

Controlling river discharge during the freezeup period can reduce freezeup ice jams and related flooding. Also, by minimizing the volume of ice formed over the course of the winter, the severity of breakup ice jam flooding can be reduced. The operational methods and objectives are similar to those described in the previous section. On smaller, steeper pool–riffle rivers, flow may be reduced at an upstream dam to allow an ice cover to form on downstream reaches, either naturally or behind an ice-retention structure, such a weir or boom.

In 1982, the Pittsburgh District of the U.S. Army Corps of Engineers installed an ice boom on the Allegheny River immediately upstream of the Oil Creek confluence at Oil City, Pennsylvania, to initiate a stable ice cover and reduce the volume of frazil deposited in the confluence area each winter. Before the boom was installed and an ice control weir built on Oil Creek in 1989, the freezeup ice jam on the main stem Allegheny often blocked the breakup ice run on Oil Creek, resulting in an ice jam at the creek confluence and severe ice jam floods in Oil City.

Successful performance of the boom depends on flow reductions at the Kinzua Dam, located on the Allegheny, 106 km upstream, during the initial ice-formation period. At the average winter discharge of about 200 m^3/s, conditions at the boom site are unfavorable for ice retention, with a velocity of about 0.61 m/s and a Froude number of about 0.14. Through analysis of field observed data, Daly and Gooch (1994) found that, since 1988, a 100% ice cover typically forms behind the boom when average daily air temperature is below about –8°C, and Allegheny River discharge upstream at West Hickory, Pennsylvania, is below about 85 m^3/s (Fig. 3). Within this flow range, the average water velocity at the boom is about 0.40 m/s and the Froude number about 0.1. The information shown in Figure 3 helps water controllers at the Pittsburgh District time the flow cutback at Kinzua Dam. The timing and magnitude of the flow cutback for ice control must be weighed against other regulatory objectives, such as providing flood storage capacity and maintaining in-stream flow minimums for fish.

Early winter flow control for winter navigation

Most of the major rivers in the U.S. with winter navigation are controlled by stage-regulated lock and dam projects on their main stems, with discharge-regulated flood control projects on their tributaries. Although flow control for ice cover formation has potential benefits to winter navigation, there are few, if any, documented cases of its use. For rivers with winter-long navigation, the

(11) Circled numbers indicate Lock and Dam numbers

Figure 4. Major waterways with winter navigation in the United States.

best ice management strategy is to rapidly form and maintain stable ice covers along the margins of a smooth-sided navigation channel (Tuthill 1998). This section examines current flow regulation and its effect on ice cover formation on the upper Mississippi and Illinois Rivers, as well as the potential for flow control for ice cover formation on the Ohio River. The Illinois Waterway is the preferred winter navigation route in the Midwest because ice conditions are relatively less severe than on the upper Mississippi. The upper Mississippi is closed to winter navigation above Lock and Dam 20, whereas the entire Illinois Waterway and Ohio River remain open to navigation all winter. Figure 4 shows these rivers and the locations of major navigation dams.

Illinois Waterway and Upper Mississippi River

Early winter flows on the Illinois Waterway and Upper Mississippi River are typically low and relatively steady, creating ideal conditions for the formation of smooth ice covers. Winter navigation may delay ice cover formation by continually re-breaking the ice cover on the navigation channel and preserving open water areas where frazil ice can be produced. The broken ice may jam at channel constrictions impeding navigation, or accumulate and cause problems upstream of locks and dams. These issues are addressed in the *Mid-winter Period* section, as is ice passage at navigation projects during that time.

On the upper Mississippi and Illinois River basins, discharge-controlled tributary inflow accounts for only a small portion of the total main stem discharge during the freezeup period. Table 2 shows average winter flows from the two major discharge-controlled tributaries of the upper Mississippi below Rock Island. These data indicate that retaining all reservoir outflow during the ice-formation period would reduce the main stem discharge by only about 5%.

Table 2. Major discharge-regulated tributaries of the Upper Mississippi River.

Tributary	Winter average discharge (Dec.–Jan.–Feb.) near confluence (m^3/s) Tributary	Mainstem	Q trib/ Q mainstem (percent)	Tributary drainage area (D_a) at at mouth (km^2)	Flood-control reservoirs	Total controlled D_a (km^2)	Portion of total D_a (percent)
Des Moines River	82	1086	7.5	38,900	Saylorville Lake Red Rock Lake	15,140	39
Iowa River	32	1086	2.9	10,370	Coralville Lake	8480	80

The potential for reducing Illinois River discharge by storing water during freezeup is even more limited. Even if tributary flow reductions were deemed beneficial for forming ice covers on the main stem, it is unlikely that such reductions would significantly affect ice processes because the tributary flow amounts to but a small fraction of the main stem flow.* On these waterways, tributary flood control reservoirs are typically drawn down in the fall and maintained at low levels during the winter in anticipation of spring runoff events. To maintain storage capacity, reservoir inflow during winter typically equals outflow. Even if discharge-controlled tributary inflow did represent a significant portion of the main stem river flow, it would probably be difficult to convince water controllers that the ice-control benefits of retaining water would justify the lost flood storage capacity.

Ohio River

Early winter discharge and water velocity can be much higher and more variable on the Ohio River than on the Illinois and upper Mississippi, even though 30% of the total discharge from the Ohio basin upstream of Pittsburgh is controlled. The Ohio River has experienced a number of severe ice years, including 1918, 1940, 1948, 1963, 1971, 1977, 1978, and 1979. The worst recent winter was 1977–78, when a combination of extreme cold and high early December discharge produced heavy ice on the river. At many locations, water velocity was high enough to form shoved ice covers and jams, impeding navigation. A massive thaw with rain in late January resulted in breakup ice jams throughout the river system and caused what later became known as the "Markland Dam Disaster," described in a later section of this report.

A study by Jain et al. (1993) examined the possibility of controlling flow at tributary reservoirs in the upper Ohio basin to promote rapid formation of juxtaposed ice covers and minimize frazil production. Numerical models simulated ice cover formation downstream of Pittsburgh on the Montgomery and Hannibal pools, predicting water cooling, frazil growth, ice transport, and ice cover progression, under a variety of air temperature and river discharge scenarios. The progression model assumed that juxtaposition of floes would occur only if the Froude number at the upstream edge of the ice cover did not exceed 0.05. The study found that optimal discharges existed for minimizing the time required to form ice covers on the two pools. A generalized case was developed to determine the minimum time to form an ice cover for a range of downstream depths, pool lengths, river bed slopes, and average air temperatures.

In spite of the potential for severe ice events, a general lack of serious ice on the Ohio River from 1980 to the present has dampened any interest in flow control to manage ice on that river system.* If an interest did arise for basin-wide flow control to manage Ohio River ice, Corps water controllers at the Ohio River Regional Office in Cincinnati could use their FLOWSED unsteady flow model to schedule reservoir releases to create optimal hydraulic conditions for ice cover formation. Similarly, the St. Louis and Rock Island Districts are set up with the UNET model (U.S. Army 1997), which has the added advantages of an ice cover option and an ice cover progression routine.

MIDWINTER PERIOD

During the midwinter period, flow-control methods can alleviate ice problems faced by the

* Personal communication with William Koellner, Chief of Water Control, Rock Island District, U.S. Army Corps of Engineers, Rock Island, Illinois, April 1998.

* Personal communication with Ronald Yates and George McKee, Water Control Center, Ohio River Division, U.S. Army Corps of Engineers, Cincinnati, Ohio, April 1998.

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hydroelectric and the navigation industries, reduce upstream and downstream ice jam flood problems, and minimize disruption of municipal water supplies and winter fish habitat. This report defines the midwinter period as the time between the appearance of a stable ice cover and the onset of the final breakup period.

Midwinter flow manipulation: Hydroelectric production and ice jam flood control

After an ice cover has formed, hydroelectric operators strive to maintain intact ice covers in the reaches upstream and downstream of their projects until the onset of the final breakup period. In some cases, limiting the magnitude and rate of flow changes at the dam can preserve a river ice cover. Careful regulation of the dam outflow minimizes the amount of stage change in adjacent reaches. As a rough rule of thumb, an ice cover will break up if the stage increases by three to four times the ice thickness above the freezeup water level (Donchenko 1978). Many other factors are involved, however, such as the ice's condition and strength before breakup, channel geometry, and the rate of stage rise (Beltaos 1984, Ferrick and Mulherin 1989). The negative effects of midwinter breakups include ice jam flooding and the reappearance of open water reaches for frazil production. Once the midwinter ice cover has formed, the large hydroelectric projects on the St Lawrence River and in northern Canada return to a relatively steady daily flow, similar to the open water discharge level. This flow increase following ice cover formation significantly smoothes the underside of the ice cover, decreasing its hydraulic resistance with time.

Where large diurnal fluctuations are required to meet hydroelectric peaking demands, it may be difficult or impossible to maintain an intact ice cover, particularly in the reach downstream of the project. Operators may be forced to limit the magnitude of their daily peak discharge to avoid downstream ice jam flooding. The following examples of Oahe Dam on the upper Missouri River, and Whitehorse Rapids on the Yukon River illustrate the difficulties of meeting peak hydroelectric demands while avoiding ice jam flooding. Timely diversion cutbacks can avert ice jams at hydroelectric projects that withdraw a major portion of the total river flow. The projects on the Upper Niagara River at Niagara Falls, New York, are an example.

Missouri River: Oahe Dam, Pierre, South Dakota

Oahe Dam, which is operated by the U.S. Army Corps of Engineers, is located on the Missouri River, 10 km upstream of the city of Pierre, South Dakota. To meet hydroelectric demands, outflow from Oahe Dam on the Missouri River fluctuates daily between about 280 and 900 m^3/s, within a maximum range of 0 to 1560 m^3/s. Each winter, a sheet ice cover forms downstream of Pierre, on the pool above Big Bend Dam. During extremely cold periods, a freezeup ice jam may progress from the head of the pool, past Pierre, as far upstream as Oahe Dam. The presence of this jam, combined with the daily peaking operations at the dam, can result in flooding of the low-lying portions of the city.

Unfortunately, the extreme cold that causes the worst ice jam conditions at Pierre coincides with regional peak electrical demand, complicating the decision to cut back releases from Oahe Dam. Although no hard and fast rule exists, prior to 1995, operators typically cut back the peak flow to about 710 m^3/s once water levels exceeded defined "alert stages" at two river gages located within the developed area of the city. It is possible that riverbed aggradation at the head of the Big Bend Pool has exacerbated the ice jam problem at Pierre in recent years.

Daly et al. (1997) analyzed field data and used numerical hydraulic models to develop separate ice-affected stage frequency curves based on cutbacks to 710 and 990 m^3/s once the alert stages at Pierre were exceeded. The analysis used actual and adjusted historical hourly flows from selected "worst-ice" periods during the winters of 1967 to 1995. Additional stage frequency relationships were developed for estimated future aggraded channel conditions. The study provided the Corps of Engineers with guidance on flow control as a tool for ice jam flood mitigation. The work also produced estimates of the frequency and duration of future flow cutbacks, as shown in Figure 5.

Yukon River: Whitehorse Rapids, Yukon Territory, Canada

The Whitehorse Rapids Power Station located just upstream of Whitehorse, Yukon Territory, provides the city with electricity. To maintain the downstream ice cover and avoid ice-related flooding, winter outflow from the plant is limited to 60% of its 276-m^3/s capacity, and daily peaking flows are limited to within 10% of the daily average flow. Through numerical modeling and a pro-

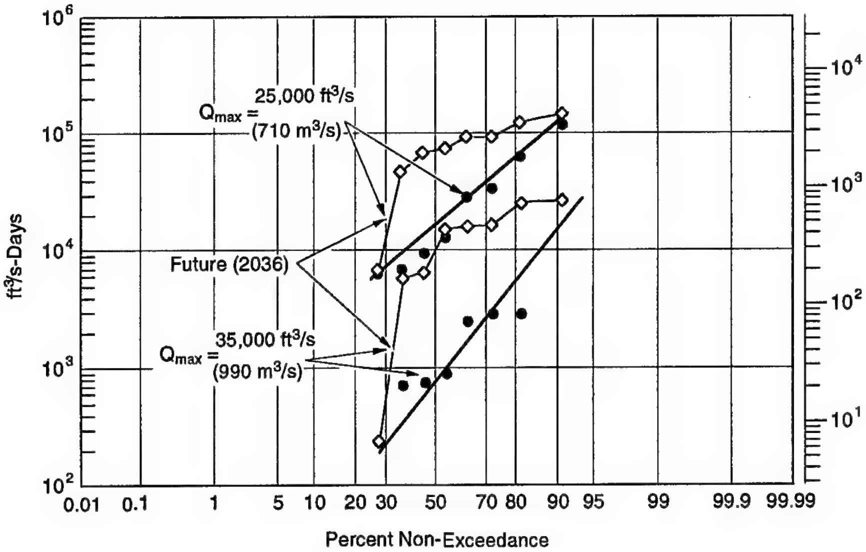

Figure 5. Annual probability of flow constraints in m^3/s-days and ft^3/s-days for future and existing conditions at Oahe Dam, Pierre, South Dakota. (After Daly et al. 1997.)

gram of field tests, Breland (1995) concluded that it would be possible to increase the winter outflow to 83% of the plant capacity without adversely affecting downstream ice conditions, or increasing the flood risk to low-lying areas in Whitehorse. The ICESIM* model was used to first simulate ice cover formation over a range of discharges, then to calculate water surface profiles resulting from different peak flow levels. Field observations during the winter of 1994 found the model to be a reasonable, though somewhat conservative, predictor of stage because the actual river ice proved to be smoother and thinner than the ice cover predicted by ICESIM.

Based on field test results, Breland found that large increases in flow are possible once the ice cover has been given time to smooth. The magnitude of this increase depends on the observed ice conditions of any given year and it should not exceed the ice cover's ability to flex vertically without breaking up. The flow increase should not force significant water flow on top of the ice. Breland recommended that the water levels resulting from the increase in discharge should not exceed the peak water levels observed during the ice-formation period. Finally, the flow increase should not be great enough to fracture, shove, or cause breakup of the ice cover.

* Acres American, Ltd., developed the ICESIM model.

Upper Niagara River:
Niagara Falls, New York

On the Upper Niagara River, early to midwinter ice jams have historically caused flooding and interfered with hydroelectric production. The New York Power Authority's (NYPA) Niagara Power Project in the U.S. and the Ontario Hydro (OH) stations in Canada have a combined generating capacity of about 4700 MW and can potentially divert as much as 4730 m^3/s of the total average river flow of 5660 m^3/s. However, the 1950 Niagara Treaty between the U.S. and Canada limits the total diversion flow at any particular time.

Ice jams on the Upper Niagara River result from storm surge events that break up the ice cover on the eastern portion of Lake Erie and drive ice over the Lake Erie–Niagara River ice boom. The surges can raise the lake level at Buffalo by up to 2 m and nearly double the water discharge in the Upper Niagara River. It takes about 12 hours for the ice to travel the 56 km from Lake Erie to the power plant intakes, located on the banks of a relatively shallow reach of the river above Niagara Falls known as the Grass Island Pool (Crissman et al. 1994). Figure 6 shows an ice jam in front of the NYPA intakes in February of 1964.

Studies by NYPA (1998) examined the ice and flow processes that lead to ice stoppages and jams on the Upper Niagara River. The approach com-

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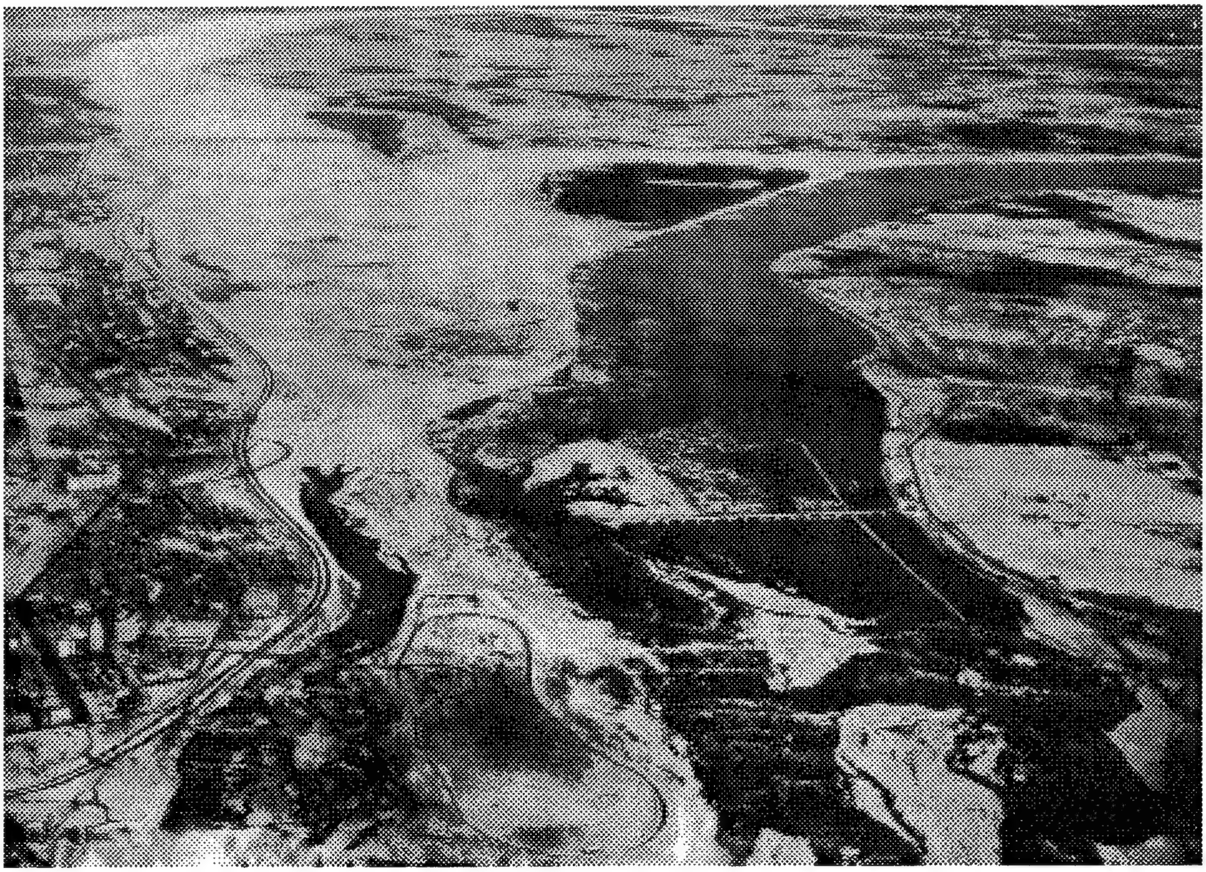

Figure 6. Ice jam at the intakes of the NYPA Niagara Falls Power Project on the Upper Niagara River. (Photo courtesy of P.A.S.N.Y.)

bined analyses of historical ice events with the use of physical and numerical hydraulic models (Shen and Su 1997) to assess operational and structural alternatives to mitigate ice jams. The numerical modeling results indicated that, under certain lake ice run scenarios, ice stoppages and jams in the vicinity of the NYPA intakes might be prevented or at least delayed by altering the schedules for diversion flows. The studies found that for long-duration (more than 24 hours), high-volume lake ice runs, ice jams are likely regardless of the hydropower diversion flows.

As part of their ice mitigation program, NYPA and OH have developed an extensive ice monitoring and ice management program that continuously informs project operators of ice conditions and provides advance warning of lake ice runs. Water levels and flows are monitored and displayed graphically for the operators. Low-light-level television cameras are used to monitor ice conditions near the intakes. In addition, a marine radar system continuously maps the ice surface in the vicinity of the NYPA intakes and is used to estimate ice concentrations and identify areas of moving or stopped ice. The radar is especially valuable at night when other means of observing ice near the intakes are not possible. Finally, video cameras, mounted on the roof the Marine Midland Center in Buffalo, continuously monitor ice conditions in the vicinity of the Lake Erie–Niagara River ice boom (Crissman and Lalumiere 1997). Much of this information is disseminated via computer networks to operators at the NYPA and OH power plants.

Midwinter flow control and winter navigation

Most of the winter navigation in the northern U.S. takes place on rivers with stage-regulated navigation dams, such as the Illinois, Ohio, and upper Mississippi Rivers. During periods of heavy ice, winter flows on the Illinois and upper Mississippi are typically low, and relatively steady. At these projects, operators must clear brash ice from the upstream approach to the locks and move the ice through gates past the dam.

Figure 7. Accumulation of broken ice upstream of Lock and Dam 26, 11 February 1966, Alton, Illinois.

Because of the low flow velocities found in pool areas, conveying ice from the lock approach to the dam gate can be difficult, particularly if the ice pieces are frozen together. Opening the gates wide for a short time can draw brash ice from the lock approach area to the gates. However, maintaining minimum pool depths for navigation and satisfying hydroelectric generating demands during low-flow winter periods can severely limit the available flow for ice passage. The ice clearing efforts of workboats or free towboats complement gate openings for ice passage, and many projects depend on the navigation industry in this regard.

Through a survey, Zufelt and Calkins (1985) identified 75 facilities that experienced ice accumulations in their upper lock approaches and 68 facilities that reported difficulty passing ice over dam spillway gates. Nearly all of the structures on the upper Mississippi, Illinois, and Ohio River systems appeared on the lists, indicating the universal nature of these problems on northern waterways.

Most of the structures on the main stem Ohio River are equipped with overflow gates installed in the upstream bulkhead slots of the auxiliary lock chambers. Under normal winter flow conditions, these gates draw ice away from the upstream approach of the main lock and pass it through the auxiliary lock. There are two types of gates. The first, called "emergency gates," are of a split leaf design with adjustable heights. The second type consists of 33-m-wide by 2.7-m-high bulkheads that are lowered into position by the service bridge crane. The top "skimmer bulkhead" is specially designed for overflow. To pass ice at higher flows, adjacent tainter gates must be opened to substantial height to draw ice beneath. At these openings, under low tailwater conditions, scour can be a problem at some of the older projects with inadequate bed armor.

The projects on the upper Mississippi are not equipped with emergency gates in auxiliary locks, although this ice passage solution has been considered (Zufelt et al. 1993). Ice passage operations at Lock and Dam 26 at Alton, Illinois, are described below, along with gate operations for ice passage at Starved Rock, Dresden Island, and Peoria Locks and Dams on the Illinois Waterway.

Mississippi River: Lock and Dam 26, Alton, Illinois

Lock and Dam 26 is a major hub for winter navigation, connecting the middle Mississippi, upper Mississippi, and Illinois Waterway. Completed in early 1989, the Melvin Price Lock and Dam replaced the old Lock and Dam 26. Midwinter thaws following extended cold periods would cause the ice cover to fail and pile up against the old dam, as shown in Figure 7. The only solution was to open a number of the 12-m-wide tainter gates 3–4

Figure 8. Passing ice over the upstream lift gate of the main lock at Melvin Price Lock and Dam on the Mississippi River.

m to cause a sudden drop in pool level that would break the ice free from the dam and shores. This ice-clearing operation depended heavily on assistance from navigation and it had to happen when there was sufficient river discharge to compensate for the outflow through the dam.

The ice passage capability of the new Melvin Price Lock and Dam is greatly simplified and improved compared to the old structure. Ice is now passed over the upstream lift gate of the centrally located main lock, as shown in Figure 8. In addition to flow over the gate, the upstream filling valves are partially opened to help flush the ice through the lock chamber. The objective is to continuously clear ice from the navigation channel between lockages without disturbing the adjacent sheet ice. Warming and rain can still break up the sheet ice cover, requiring tainter gate openings, in addition to the lock lift gate, to clear the upstream pool.*

Illinois Waterway: Starved Rock, Dresden Island, and Peoria Locks and Dams, Illinois

At Starved Rock Lock and Dam, brash ice that accumulates in the lock approach must travel laterally 180 m along face of the dam, past powerhouse intakes, to reach the nearest two tainter gates. Opening both 18-m-wide gates 1.5 m creates a discharge of about 420 m^3/s and sufficient surface velocity in the 5-m-deep pool to clear accumulations of loose brash. Discharge at this gate opening is well above winter average river flow, so the operation must as brief as possible. Often, the ice pieces are frozen together, and ice clearing relies on towboat propeller wash to break up the ice and move it towards the gates. Physical model studies at CRREL found that ice passage at Starved Rock could be improved by locating an angled submergible gate adjacent to the lock (Tuthill and Gooch 1997).

Upstream of Starved Rock on the Illinois Waterway, at Dresden Island Lock and Dam, a similar scheme of intermittent gate openings is used to clear the lock approach area of ice. Ice passage problems at Dresden Island are less severe than at Starved Rock because the ice is thinner and less abundant, owing to upstream thermal inputs.

Downstream of Starved Rock, at Peoria, Illinois, a 18-m-wide submergible tainter gate located alongside the lock has proven extremely effective at diverting and passing the ice pushed ahead of downbound tows (Fig. 9).

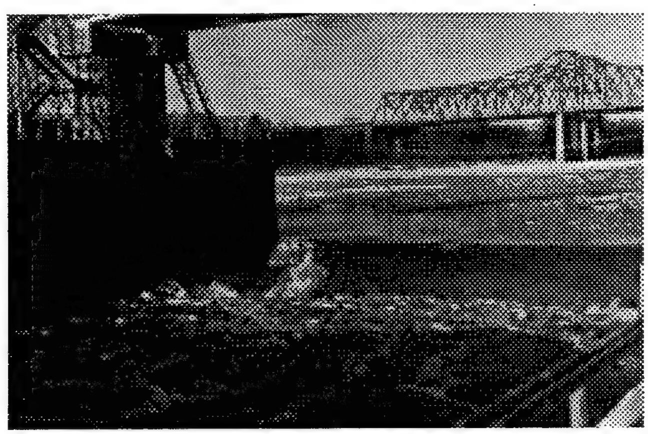

Figure 9. Submergible gate at Peoria Lock and Dam on the Illinois Waterway.

Midwinter flow regulation: Water supply and ice jam formation

Release schedules from multipurpose reservoirs on western U.S. rivers often balance summertime irrigation and recreational needs of upstream water users against the need to provide for downstream navigation depths and water supply requirements. This task is most difficult during periods of extreme drought, when low flows may reduce ice conveyance capacity and cause freezeup ice jams. As water impounds upstream of the jams, the resulting flow deficits downstream may uncover or hinder the operation of water intakes. The lowermost 1390 km of the

* Personal communication with lockmaster Thomas Miller, 12 January 1999.

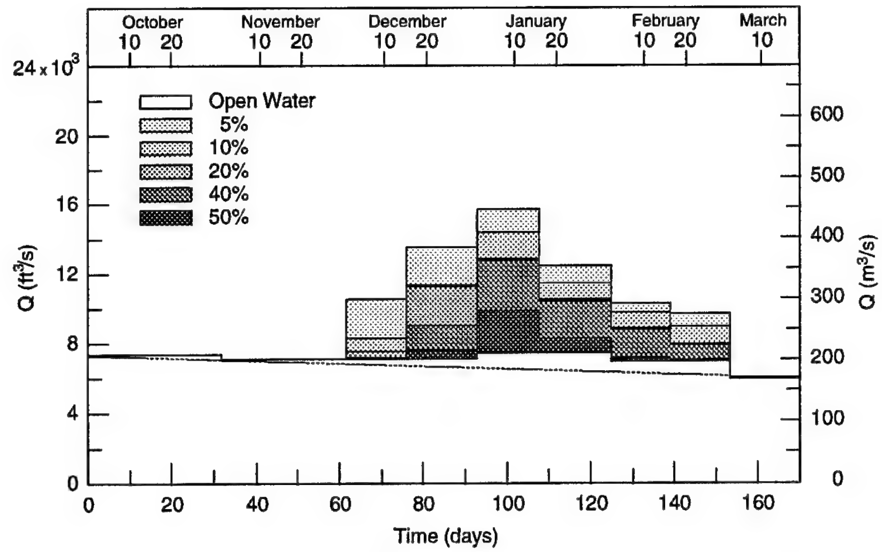

Figure 10. Minimum releases from Gavins Point Dam on the Missouri River for a range of exceedance probability ice events. (After Wuebben et al. 1992.)

Missouri River below the Gavins Point Dam experiences this problem.

The severe drought conditions of the late 1980s led the U.S. Army Corps of Engineers to investigate the effects of ice formation on flow regulation on the lower Missouri River downstream of Gavins Point Dam. The study by Wuebben et al. (1992, 1995) used a probabilistic approach to develop a method for adjusting planned release schedules from Gavins Point Dam to compensate for the flow deficits caused by ice jams. A statistical analysis of weather records and a review of historical ice and low-flow events allowed empirical estimates of future ice conditions to be made, based on predicted weather and planned releases. The study included both long- and short-term planning approaches that allow operators to select an ice-affected release schedule, based on an acceptable level of risk. Figure 10 is an example of a long-term planning tool produced by the study. For an ice event with a given exceedance probability, a water-control planner can select a release schedule to avoid downstream discharge deficits.

Midwinter flow regulation and fish habitat

Winter reservoir operation influences the natural ice regime on rivers, and may affect fish survival. In particular, hydroelectric peaking cycles can affect ice processes for great distances downstream. Where a steady flow might produce a sheet or a juxtaposed ice cover on a given reach, a peaking flow hydrograph might result in a shorter, thicker cover at a more downstream location. The spatial extent and type of ice cover on a reach directly affects the stage and available channel area for fish habitat, particularly in wide, shallow rivers. A fluctuating flow pattern may result in premature or repeated ice breakups over the course of the winter, and this may have a negative effect on the overwintering habitat for fish. The Green River in Utah is an example.

The Green River near Vernal, Utah, is habitat for several endangered fish species, including the Colorado squawfish, the razorback sucker, the humpback chub, and the bonytail. About 160 km upstream of Vernal, near the Wyoming border, a hydroelectric project at the Flaming Gorge Dam follows a daily peaking schedule that fluctuates between 23 and 110 m^3/s, depending on demand. Recent studies have suggested that ice movement and shoreline scouring from ice breakup can be undesirable for the overwintering habitat of juvenile endangered fish species (USFWS 1992). Daly et al. (1997) examined the effect of daily fluctuations from the Flaming Gorge Dam on ice cover formation and stability in the study reach hosting the endangered fish species. The study included research on historical ice and hydrometeorological data, a field observation program during the winter of 1996–97, and a computer simulation of ice cover formation, calibrated to field-measured data. Field observations and ice measurements

were made during a 20-day steady flow period, and repeated for a 4-day period with a daily peaking pattern. The study concluded that the daily peaking pattern had little effect on the overall annual pattern of ice cover progression on the river. However, the fluctuating flows did cause a shoved type of cover at locations in the upstream, steeper portion of the study reach, where a thinner juxtaposed cover had existed under steady flow conditions.

Midwinter reservoir levels and ice jam flooding

Winter reservoir operations may also influence the ice regime at upstream locations. The winter pool level at water storage reservoirs can influence the location and severity of freezeup ice jams on tributary rivers and streams. On some western reservoirs, winter pool levels have been raised substantially to meet increasing water demands. This change may cause freezeup ice jams on feeder streams, or displace jams upstream from their historic locations. The South Fork Shoshone River that flows into the Buffalo Bill Reservoir near Cody, Wyoming, is an example.

In response to increased water storage demand, the Buffalo Bill Reservoir raised its winter pool in 1995 to an elevation 13 m above the average pool level of the previous 19 years. The winter of 1996–97 saw consistently below-average air temperatures accompanied by above-average discharge on the South Fork Shoshone River. A serious freezeup ice jam flooded properties several miles upstream of the reservoir where few recent ice jam floods had been reported. Because of the short period of record and limited historical data, it was difficult to determine the relative significance of the severe cold and the higher reservoir elevation with respect to the ice jam severity in 1996–97. However, the higher reservoir elevation probably did have some influence (Tuthill 1997).

BREAKUP PERIOD

Flow control and project operation can affect the location and reduce the severity of ice problems during the breakup period. Although the subject of much research, ice processes during the breakup period are more complex and less well understood than ice formation or those during the midwinter. Ashton (1986) and Beltaos (1995) describe much of the research to date, as well as the factors that influence the timing, location, and nature of river ice breakup.

Breakup ice jams often form in reaches that change from steeper to milder water surface slope, such as river to lake or pool confluences. If the lake or pool level can be regulated, it may be possible to influence the ice jam location, but the effect of water level change on ice jamming is often difficult to predict. Operation of river and reservoir dams can affect the timing and severity of breakup as well by storing water to reduce the rate of hydrograph rise and the peak flow in downstream reaches. This strategy may delay breakup or at least reduce its severity.

It may be possible to control water level at the time of ice cover formation to mitigate breakup severity. Donchenko (1978) predicted that the ice cover would release when stage exceeds a level of three to four ice thicknesses above the freezeup water level. Based on this, one strategy is to raise the freezeup water level, then lower the water level before breakup, creating some in-channel storage and delaying breakup. In contrast to flow control to delay breakup, Ferrick and Mulherin (1989) proposed using reservoir releases to prematurely break up a section of ice cover to serve as a receiving area for ice from the subsequent natural breakup. Once an ice jam has formed, it may be possible to decrease outflow from upstream dams to prevent or reduce resultant ice jam flooding. Finally, river structures can be operated during extreme breakup events to prevent damage to the structure while minimizing ice effects and jam flooding in upstream and downstream reaches.

Controlling ice jam location

Breakup ice runs on rivers often stop when they encounter an intact sheet ice cover on a pool or reservoir. If the pool level can be regulated, raising or lowering the water level will move the head of pool location and the ice jam initiation point upstream or downstream, respectively. In many instances, raising the water level in a reservoir will displace the breakup jams on tributaries upstream. There are also numerous examples of breakup jam problems moving downstream following reservoir lowering or the removal of old mill dams on small rivers. A strategy for displacing ice jam location downstream is to lower the pool level before breakup takes place. This technique has the added advantage of providing a storage area for the breakup ice. Lowering pool elevation may have unexpected results, however. The resulting slope may be steeper and the jam thicker, causing ice jam flood levels in the upstream problem area equivalent to the higher-

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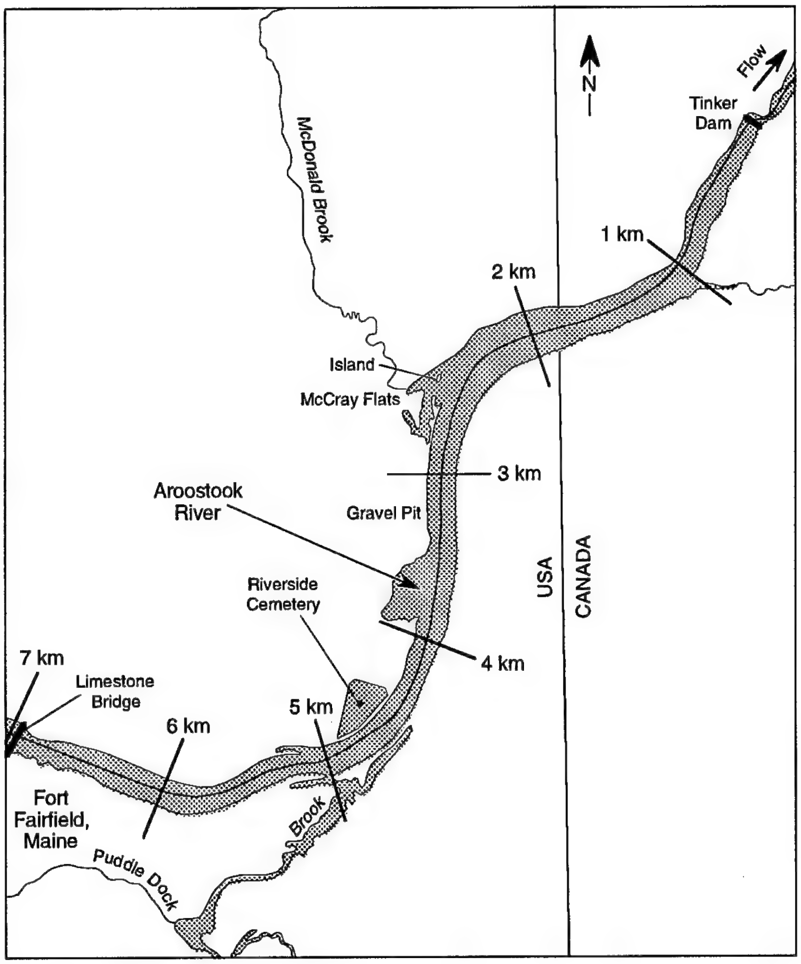

Figure 11. Aroostook River from Tinker Dam upstream to Fort Fairfield, Maine. (After White and Acone 1995.)

reservoir case. Also, the decreased flow area or the presence of sediment deposits in the original head of the pool area may stop the ice run before it reaches the intact ice cover of the lowered pool.

A study by White and Acone (1995) examined the relationship between dam operation and upstream ice jamming processes on the Aroostook River in northern Maine. The ice runs on the Aroostook typically stop at the head of the Tinker Dam pool, a small hydroelectric facility located 6.5 km below Fort Fairfield (Fig. 11). The town has experienced 18 damaging ice jams from 1927 to 1995. A bascule gate regulates pool level, and the daily drawdown cycle is 1.2 to 1.5 m. Within the typical 425- to 570-m^3/s breakup flow range, the pool height difference between a fully open and fully closed gate is only 10 to 20 cm. Under the current operating procedure, the gate is up both during the ice-formation period and breakup events.

Using the HEC-2 backwater model (U.S. Army 1990), the authors found that lowering the pool during the ice-formation period would increase upstream water velocity and Froude number at some locations beyond the range of ice cover formation by juxtaposition. The resulting shoved ice cover would be thicker, possibly causing the breakup ice run to stop farther upstream than under the current operating scheme. During a midwinter field visit, thick deposits of frazil were measured 2.5 km above the dam, in the same general area as the observed stoppages of breakup ice runs. Using the frazil transport and deposition theory developed by Shen and Wang (1995), the authors predicted that maintaining a steady rather than a peaking flow during the freezeup period would result in frazil deposition farther upstream. The upstream frazil deposits could cause the breakup ice run to stop at a location closer to Fort Fairfield, increasing the ice jam flood threat. The

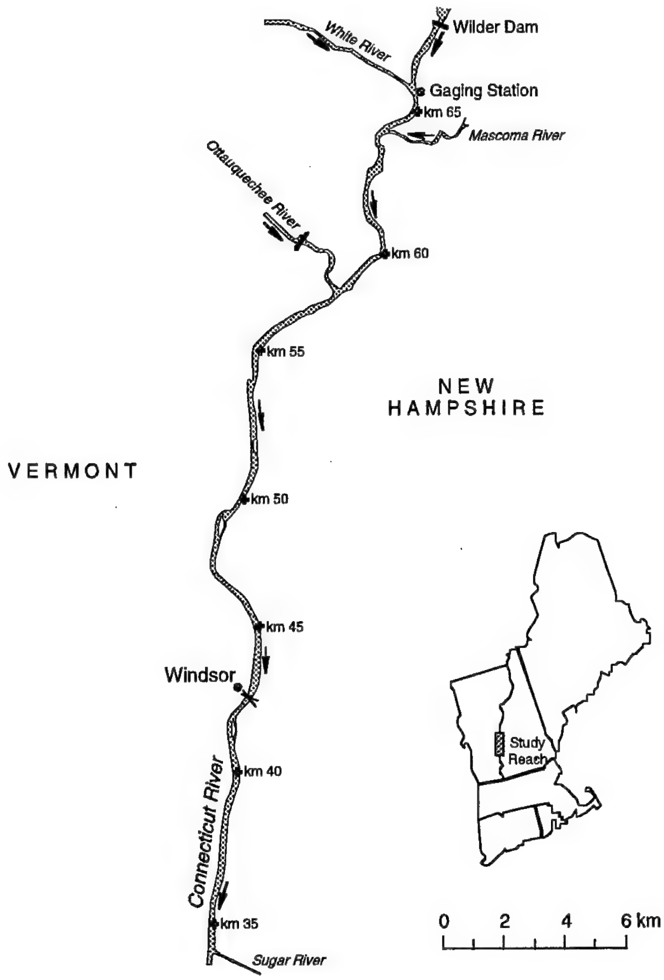

Figure 12. Connecticut River below Wilder Dam. (From Ferrick and Mulherin 1989.)

authors used an equilibrium ice jam model to predict that lowering the pool during breakup would cause a slight increase in ice thickness at a reference location 3.2 km downstream of Fort Fairfield. Based on this result and the frazil deposition analysis, the study concluded that lowering the winter pool at Tinker Dam would not reduce the ice jam flood risk at Fort Fairfield.

Controlling timing of breakup

In some cases, flow regulation can influence the timing of the final breakup on rivers. Dynamic and destructive breakups result when rapid runoff enters rivers with competent ice covers in late winter or early spring. Controlling outflow from a dam or system of dams can dampen the hydrograph in downstream reaches, delaying or reducing the severity of breakup. This delay may give the ice a chance to weaken and melt in place, reducing the possibility of ice jam flooding when the ice finally does release. It may be possible to operate a series of river dams to encourage a downstream-to-upstream breakup progression and reduce ice jam potential. Flow regulation for breakup control has potential benefits at river confluences. One strategy is to delay breakup on one stem of a river until the other branch is ice-free. The following example illustrates the opposite approach: regulating flow to cause a controlled breakup on the main stem of a river to reduce ice jam severity when a tributary releases its ice.

Ferrick and Mulherin (1989) developed a one-dimensional model to simulate dynamic ice breakup on rivers. The model was used to assess the feasibility of regulating flow to control breakup on the Connecticut River in New Hampshire. Figure 12 shows the study reach. The most destructive breakup ice jams on the Connecticut occur near Windsor, Vermont, after the uncontrolled White River releases its ice, breaking up the ice cover on the main stem. The authors theorized that ice jam severity could be decreased by initiating an early breakup on the Connecticut River through planned releases at three dams. Following calibration to an observed ice-breakup event, the model predicted the occurrence and non-occurrence of breakup, as well as the length of the broken ice cover for a variety of input flow hydrographs and a range of initial ice thickness and ice strength values. The method was validated through a series of field experiments done on the Connecticut River in the early 1990s.*

Passing ice at structures during extreme events

During ice breakup, operators of river dams may have to pass the ice and floodwave as it arrives to avoid a number of problems. These include ice grounding in the pool and upstream ice jam flooding, thick ice buildups against dam gates preventing their operation, and ice blockages of lock approaches. Also, if the dam retains large quantities of ice, it may be difficult to pass this ice once the peak of the water wave has moved downstream.

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* Personal communication with Michael Ferrick, CRREL, September 1998.

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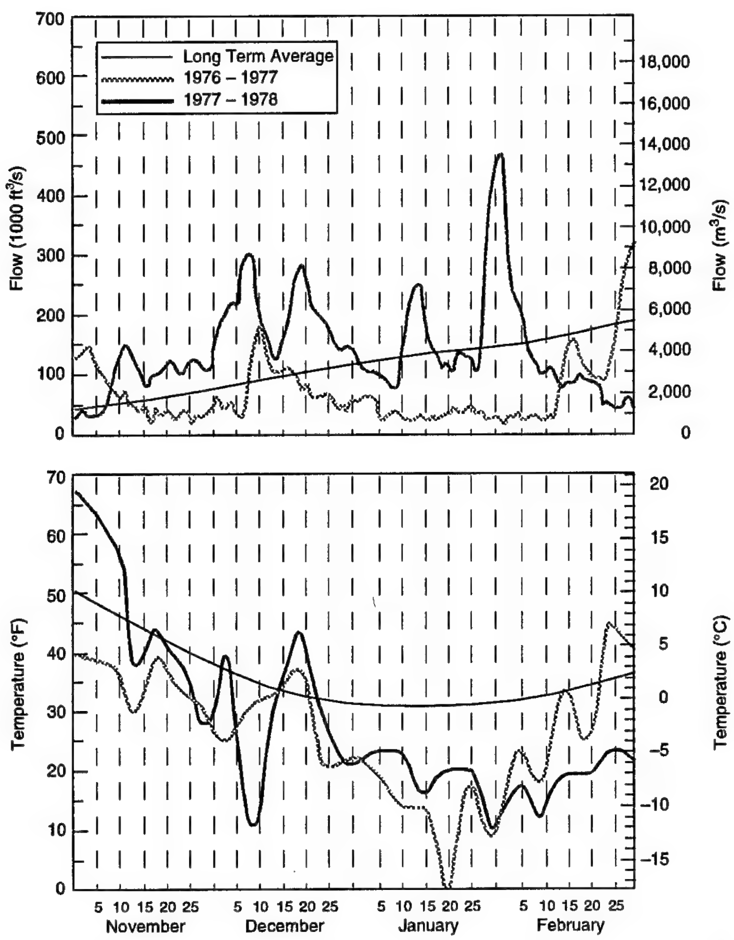

Figure 13. Ohio River discharge and air temperature at Cincinnati, winters of 1976–77 and 1977–78, compared to long-term averages. (After USACE 1978.)

Ohio River: Markland Dam, 1978

As mentioned earlier, December and January of 1978 saw high discharge, extreme cold, and record ice formation on the Ohio River and its tributaries. Figure 13 shows temperature and discharge data for the winters of 1976–77 and 1977–78. The regime of the river had been substantially altered in the previous half century by the gradual replacement of low-head wicket dams with higher, more widely spaced modern lock and dam projects. These structures pass ice either through overflow gates placed in the upstream bulkhead of the auxiliary locks or through tainter gates on the dam, sometimes lifted completely out of the water. Figure 13 shows the four-fold increase in discharge resulting from rainfall and snowmelt runoff during 25–28 January 1978. Although flow and ice was retained at storage reservoirs on tributaries, nearly all downstream ice ran throughout the Ohio River system. Late on 25 January, the rainstorm transformed into what became known as the "Blizzard of '78," hindering visibility and communication and further worsening operating conditions for the river projects and navigation. On 26 January, a substantial ice jam 26 km upstream of Markland Dam released, sweeping 19 loose barges and a towboat against the gates of the dam (Fig. 14). Following the passage of the flood wave, the ice pileup remained, blocking the lock approach and making it difficult to extricate the trapped and sunken vessels (USACE 1978).

Although uncommon, severe ice events have substantially damaged river structures. Because events of this magnitude are so infrequent, there may not be any operational experience upon which to fall back. Similar to an extreme open water flood event, the usual response at a run-of-the-river dam is to maintain a maximum gate opening to allow passage of water and ice without damaging the structure. It is also critical to coordinate operations with other projects and emergency response organizations.

The following is a compilation of extreme ice events at dams and the actions taken. Well known examples of structural damage caused by breakup ice are Markland Dam on the Ohio River in 1978, Dresden Island Dam on the Illinois River in 1982, and Safe Harbor Dam on the Susquehanna in 1996. Less well known near-disasters occurred at dams on the Clark Fork River at Missoula and Thompson, Montana, in 1995.

Illinois River: Dresden Island Dam, 1982

Upstream of Dresden Island Dam, the Des Plaines and Kankakee Rivers join to form the Illinois River. The Kankakee, a heavy frazil ice producer, has experienced many severe ice jams and ice jam floods on its lower reaches. In 1982 an ice floe, about 0.16 km² in area, released from the lower Kankakee and drifted into the Dresden Island Dam, causing $8.2 million of damage to two tainter gates. Although the usual action for avoiding severe ice impact is to pull the gates completely out of water, this was not possible because the two gates were under repair and not functional at the time.

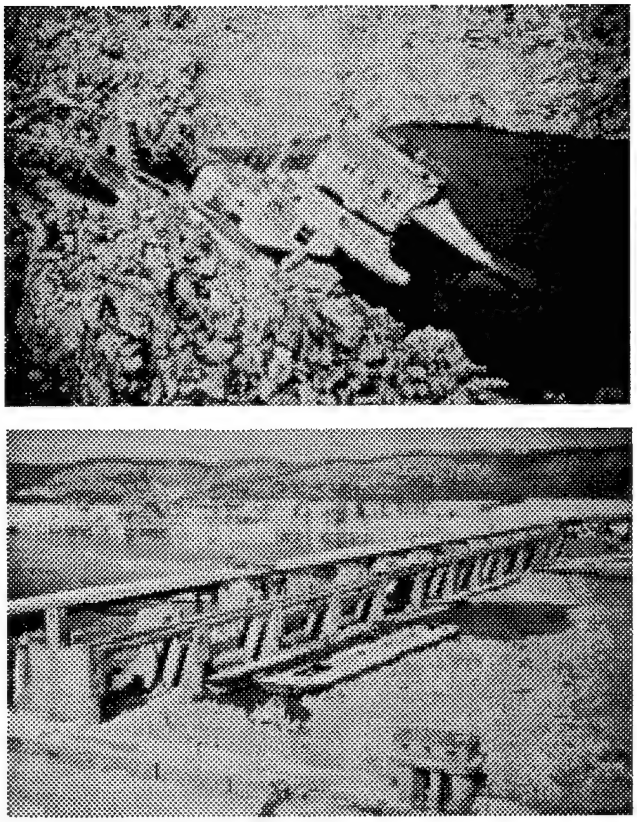

Figure 14. Towboat and barges against Markland Dam on the Ohio River, February 1978.

Susquehanna River: Safe Harbor Dam, 1996

The 1490-m-wide by 20-m-high Safe Harbor Dam on the Susquehanna River receives ice from as far upstream as 600 km on the main stem, as well as from tributaries. Under average conditions, most of the river flow passes through the 418-MW powerhouse located on the eastern side of the river, to the left of a 460-m-long ice and debris skimmer wall (Fig. 15). When river discharge exceeds the 990-m^3/s powerhouse capacity, spillway gates on the western side of the dam are opened to pass the additional water flow and break up ice.

Operators monitor ice jams that typically form at the upstream end of the 24-km-long pool but jams sometimes occur at a point 6.5 km above the dam. The aim is to maintain sufficient pool depth to keep the jams from grounding. If upstream flooding occurs, operators may try to break the jam by rapid gate openings to drop the pool and get the ice moving. The ice is flushed past the dam along the deeper western side of the channel.

In January 1996, a major ice and water surge from upstream resulted in an instantaneous discharge at the dam of 22,700 m^3/s, above a background Susquehanna River flow of 14,000 m^3/s. At the time, the pool was filled with broken ice and a 2.4-m head differential developed across the skimmer wall, overturning the 66-year-old structure for two-thirds of its length. Gemperline and O'Donel (1998) theorized that, prior to the surge, flow towards the powerhouse might have packed ice along the western side of the skimmer wall. When the surge occurred, this partial ice blockage may have delayed the stage adjustment behind the wall, causing the head differential and failure.

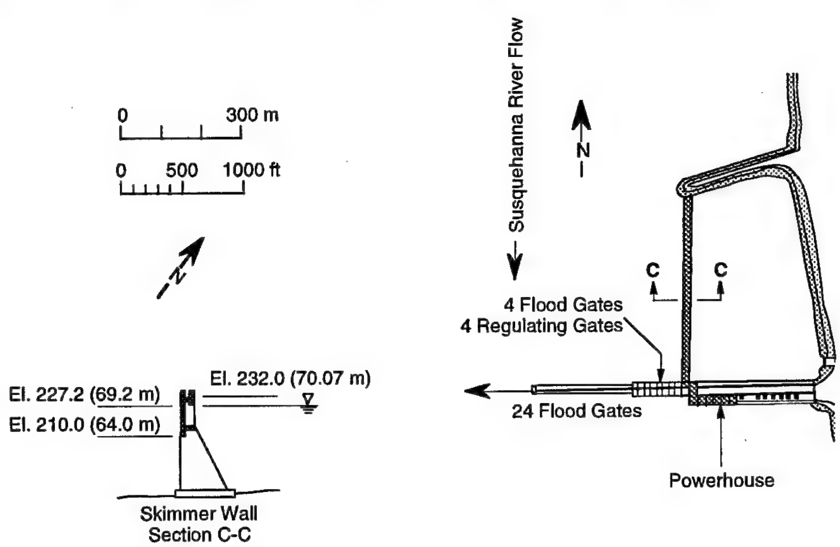

Figure 15. Plan view of the forebay and cross-sectional view of skimmer wall at Safe Harbor Dam, Susquehanna River, Pennsylvania. (After Gemperline and O'Donel 1998.)

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Clark Fork River: Montana, 1996

In February of 1996, a sudden thaw caused rapid runoff and widespread breakup of the region's rivers. Although opinions varied, local people estimated the recurrence interval for the event at 20 to 40 years. At least two dams were threatened on the Clark Fork River. On 8 February, the operators of the Milltown Dam above Missoula, Montana, prepared for a massive breakup ice run that had been clocked at 16 km/hr moving down the Big Blackfoot River, a tributary that enters the Clark Fork just upstream of the dam. This small hydroelectric project consists of a powerhouse, a single radial gate, and a spillway section equipped with trippable steel stanchions that support wooden panels. When the ice run was reported to be within 3.2 km of the dam, the operators cut out the stantions with torches to remove all potential obstacles to ice passage. The ice run stopped 2.4 km above the dam, against thick frazil deposits at the Big Blackfoot–Clark Fork Confluence.

The following day, a 14-km-long ice jam formed on the Clark Fork River, 1.6 km upstream of the Montana Power Dam at Thompson Falls, Montana. Ice watchers stationed at the toe of the jam maintained 24-hour contact with dam operators, who prepared for the jam's release by completely opening the dam's central 12-m-wide gate. On 14 February the jam broke and moved en masse towards the dam. As ice and debris passed the gate, operators successfully removed by crane, or sawed in half, large logs that caught in the gate opening. Because of these actions, damages were minor.

CONCLUSIONS

This section assesses the relative importance of existing flow-control methods to manage ice, identifying valuable areas for further research and development. Available guidance on winter flow-control methods is discussed, ranging from field observation and operational experience to the use of sophisticated numerical models. Table 3 presents flow-control objectives and methods for the ice formation, midwinter, and breakup periods, listing some of the available guidance and analytical tools.

Ice-formation period

Hydroelectric facilities possess a great deal of operational experience with controlling flow to create ice covers that help maximize electricity production. A less common, but equally effective, use of early winter flow regulation is to speed ice cover formation to reduce frazil production, which helps mitigate ice jam flooding. Although research has been reported, flow control has probably not been used to create ice covers on major U.S. rivers to facilitate navigation. A probable reason is that nearly all tributary reservoirs in the U.S. are operated primarily for flood control and few are currently authorized to alter their release schedules for the purpose of ice control. Also, retaining tributary flow during the ice-formation period might conflict with the objective of maintaining minimum depths for main stem navigation. Table 4 lists the objectives of early season flow control at the projects discussed in this report.

There exists considerable operational experience and engineering guidance for controlling flow to form ice covers. Operators at large hydroelectric facilities time flow cutbacks for ice cover formation on the basis of a combination of experience, ice observations, water and air temperatures, and water level measurements. Dam outflow may be further adjusted on the basis of the position of the upstream edge of the progressing ice cover.

In addition to experience and observation, analytical techniques exist for estimating ice cover progression as a function of water discharge and air and water temperature. These methods range from simple water velocity and Froude Number criteria and steady-state hydraulic models, such as HEC-2, to more sophisticated models such as RICE (Shen et al. 1991) and UNET with ice (Daly et al. 1997). The latter two predict ice thickness and ice edge progression for inputs of time series discharge, air, and water temperature data (Table 3).

Midwinter period

During the midwinter period, flow-control objectives are more diverse than during early winter. In the case of hydroelectric facilities, the primary objectives are maximizing generation capacity, while minimizing the chance of midwinter breakups and ice jam flooding. For navigation dams on major U.S. rivers, winter operations focus on passing ice and clearing ice from the upstream lock approaches. During low-flow winters at large river storage projects, operators may need to regulate outflow to compensate for water impounded by downstream ice jams. Finally, winter releases may need to be adjusted to satisfy in-stream needs

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Table 3. Summary of flow control objectives, methods, and guidance.

	Flow control objective	*Method and level of use*	*Operational guidance and empirical methods*	*Analytical methods: Numerical and physical models, studies*
Ice-Formation Period	Maximize hydroelectric production	Flow reductions for rapid ice cover formation, wide use.	Ice obs., T_a, T_w, Q, WSE , water vel. and Froude Number	HEC-2, UNET, RICE
	Facilitate winter navigation	Flow reductions for ice cover formation, potential use.		Jain et al. (1993)
	Control freezeup ice jam flooding	Flow reductions for ice cover formation, moderate use.	Ice obs., T_a, T_w, Q, WSE , water vel. and Froude Number	HEC-2, UNET, RICE, Daly and Gooch (1994)
Midwinter Period	Maximize hydroelectric production	Flow increases to smooth ice cover, wide use.	Ice obs., T_a, ,Q, WSE	HEC-2, UNET ICESIM, Breland (1995)
	Maintain ice cover Prevent ice jam flooding	Gradual Q changes to avoid breakups, wide use.	Limit Δ WSE to < 3 to 4 × t_i, maintain WSE at or below freezeup WSE	HEC-2, UNET ICESIM, Breland (1995) Donchenko (1978)
	Facilitate winter navigation Promote ice passage	Dam gate operation to clear ice from upstream lock approaches, wide use.	Ice obs., WSE, Q, T_a	RMA2, DynaRICE, CRREL DEM, physical models.
	Provide winter water supply and minimum in-stream flows	Increase reservoir outflow to compensate for Q deficits caused by ice jams, moderate use.	Ice obs., T_a, T_w, Q, WSE	HEC-2, statistical analysis of historic ice events and weather data, Wuebben et al. (1995).
Breakup Period	Control ice jam location	Regulate pool elevation for u/s jams, moderate use. Controlled releases to break up d/s ice, potential use.	Ice obs., T_a, Q, WSE, SWE, forecasted weather	HEC-2, UNET, rainfall and snowmelt runoff models, Ferrick and Mulherin (1989) breakup model.
	Control timing of breakup	Controlled releases to break up d/s ice, potential use.	Ice obs., T_a, Q, expect breakup when Δ WSE ≥3 to 4 × t_i, or above freezeup WSE	UNET, Ferrick and Mulherin (1989) breakup model.
	Promote ice passage and prevent structural damage	Dam gate operation to pass ice. Maintain pool depth to prevent ice grounding, wide use.	Ice obs., Q, WSE, communication networks	Physical models, Gemperline and O'Donel (1998).

T_a = Air temperature.
T_w = Water temperature.
Q = Water discharge.
WSE = Water surface elevation.
t_i = Ice thickness.
u/s = Upstream.
d/s = Downstream.
SWE = Snow water equivalent.

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Table 4. Flow-control objectives; ice-formation period.

River; structure	Maximize winter hydroelectric production	Benefit winter navigation	Control ice jam flooding
St. Lawrence River; Beauharnois Canal	Primary		
St. Lawrence River; International Section	Primary		
Jenpeg Diversion, Lake Winnipeg Regulation	Primary		
La Grande River Complex	Primary		
Allegheny River; Kinzua Dam			Primary
Illinois River Navigation Dams			
Upper Mississippi River Navigation Dams			
Upper Ohio River Dams and Flood Control Projects		Possible	

Table 5. Flow-control objectives; midwinter period.

River; structure	Maximize winter hydroelectric production	Control ice jam flooding/ maintain ice cover	Ice flushing/ winter navigation	Water supply/ in-stream flows for fish
Missouri River; Oahe Dam	Primary	Primary		
Yukon River; Whitehorse Rapids Dam	Primary	Primary		
Upper Niagara River; Niagara Falls Diversions	Primary	Primary		
Ohio River Navigation Dams	Secondary	Secondary	Primary	
Upper Mississippi River; Locks and Dams 20–26	Secondary	Secondary	Primary	
Illinois River; Navigation Dams	Secondary		Primary	
Missouri River; Gavins Point Dam				Primary
Green River, Utah; Flaming Gorge Dam	Primary			Primary
South Fork Shoshone River; Buffalo Bill Dam		Secondary		Primary

for water supply and fish. Table 5 lists flow-control objectives at projects described in this report.

Flow-control guidance for preventing midwinter breakups and ice jams

Hydroelectric producers often must constrain the magnitude of their flow increases following ice cover formation, and limit the amplitude of the hydroelectric peaking cycle to minimize midwinter breakups and ice jam flooding. Owing to a lack of practical engineering tools for predicting river ice breakup, hydroelectric plant operators rely on observation and experience rather than theoretical methods to avoid breaking up the ice cover and causing ice jam floods. The rules of thumb that exist are not easily transferable from site to site. For example, Donchenko (1978) observed that stage must rise 3 to 4 times the ice thickness above the freezeup water level to break up the ice cover on some Russian rivers. Breland's (1995) observations on the upper Yukon River were more conservative, predicting that midwinter stage increases above the freezeup water level could produce ice jam flooding and possibly break up the ice cover.

With estimates or measurements of ice thickness and roughness, numerical models such as HEC-2 and UNET can predict ice-affected stage rise under different discharge scenarios. The likelihood of a planned flow release causing a midwinter breakup can then be assessed, based on knowledge of local ice processes or the above-mentioned rules of thumb. Further development of Ferrick and Mulherin's (1989) breakup model would improve the capability for predicting midwinter breakup and provide a flow regulation–planning tool for project operators.

Recent studies by NYPA and OH have improved the understanding of the relationship between project operations and ice jamming on the Upper Niagara River. Study results were based in part on a model developed by Shen et al. (1997) that accurately simulated ice transport and jamming under a range of operational scenarios. This model would be a useful tool in future studies

Table 6. Flow-control objectives; breakup period.

River; Structure	*Control ice jam location*	*Control timing of breakup*	*Promote ice passage at structures*	*Prevent structural damage*
Aroostook River; Tinker Dam	Secondary			Secondary
Connecticut River; Wilder Dam	Possible	Possible		
Ohio River; Markland Dam			Primary	Primary
Illinois River; Dresden Island Lock and Dam			Primary	Primary
Susquehanna River; Safe Harbor Dam			Primary	Primary
Clark Fork River; Thompson Dam			Primary	Primary
Clark Fork River; Milltown Dam			Primary	Primary

examining the effect of flow regulation on ice processes at other sites.

Flow-control guidance for passing ice at dams

Passing ice at Corps navigation structures on major U.S. rivers is one of the greatest winter operations challenges faced by the Corps. A great deal of operational experience exists, but much of this information is site-specific and not well documented. A summary and analysis of operational ice passage methods at Corps structures would be a worthwhile effort. CRREL researchers have investigated ice passage at specific sites with physical model studies using real ice. The two-dimensional model developed by Shen et al. (1998) to simulate ice jamming at the mouth of the Missouri River has potential for assessing ice passage operations at navigation structures. In addition, a discrete element model under developed at CRREL by Hopkins et al. (1998) could be adapted to simulate flow–ice–structure interactions in three dimensions.

Operational guidance for dam releases under conditions of low flow and ice

Adjusting winter release schedules from storage reservoirs to compensate for downstream ice jam formation and flow deficits is an important operational issue at some Corps structures. With the exception of the study by Wuebben et al. (1992, 1995), little guidance is available for predicting the likelihood of ice-related flow deficits and adjusting release schedules accordingly. Further work in this area would be valuable.

Breakup period

During breakup, the opportunities for managing ice through flow regulation are more limited than during the ice-formation and midwinter periods. Although there is some potential to control flow to affect the location and timing of breakup, the primary operational goals at most river projects are to pass ice as it arrives and avoid damage to the structure. Ice jam location can be controlled to some extent by regulating pool levels prior to breakup, and, in some cases, dam gates can be operated during the event to either pass or retain the breakup ice, depending on the ice-control objective. As far as the timing of ice releases, project operations may, to a limited extent, either delay or precipitate breakup. Table 6 lists flow-control objectives during the breakup period at the projects described in this report.

There is little analytical guidance in these areas, and operators rely mainly on experience. Ferrick and Mulherin's (1989) model for predicting breakup (or non-breakup) is a potentially valuable tool for forecasting the effect of a flow release on the downstream ice cover. A refinement of this breakup model or incorporation of ice-breakup routines in existing one- and two-dimensional ice transport models would be a worthwhile research direction in the field of flow control to manage river ice.

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13. ABSTRACT (*Maximum 200 words*)

This report describes flow-control methods for reducing ice problems in rivers. Objectives include reducing ice interference with winter hydroelectric production and navigation, ice jam flood mitigation, as well as ensuring minimum winter flows for fish and water supply. The winter season is divided into three periods. During early winter, the main objective of flow control is to promote the rapid formation of a smooth, stable ice cover. For the midwinter period, the aim of the river regulation is to maintain an intact ice cover and avoid premature ice breakup. During the final winter period, the goal is to minimize adverse effects of ice breakup. Examples illustrate the methods and objectives, emphasizing innovative approaches. Available flow regulation planning tools are described and valuable research directions identified.

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